

Murphy et al. Reply to the Comment by Kopeikin on “Gravitomagnetic Influence on Gyroscopes and on the Lunar Orbit”

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In [1], we point out that a gravitomagnetic term in the equation of motion used to dynamically determine the precise shape of the lunar orbit is also responsible for the “frame-dragging” precession of a gyroscope near a massive rotating body. In the former case, the gravitomagnetic interaction between the moving masses of Earth and Moon—as evaluated in the solar system barycenter (SSB) frame—leads to orbital amplitude contributions at the six meter level. Part of the gravitomagnetic interaction plays a role in producing the necessary Lorentz contraction of the orbit in this frame. In the case of a gyroscope, the same interaction between mass elements moving within the macroscopic bodies produces the gyroscope precession. The physics is the same for both, the difference being in the distribution of mass currents.

The SSB frame is chosen for lunar laser ranging (LLR) analysis for a variety of practical reasons [2]—not least of which that it is the most convenient asymptotically inertial reference frame for solar system dynamical analyses. The lunar and planetary orbits and the lunar rotation are determined by a simultaneous numerical integration of the post-Newtonian differential equation of motion and evaluation of light propagation times between the moving Earth and Moon [3].

The six-meter gravitomagnetic influences on the lunar orbit in the SSB frame appear as $\cos D$ and $\cos 2D$ signatures, where D is the synodic phase. The post-Newtonian model, as implemented in the way described above, fits decades of LLR data in these modes to 4 mm and 8 mm accuracy, respectively. Therefore, any *isolated* modification of the gravitomagnetic term is limited to $\approx 0.1\%$ the strength prescribed by general relativity [1].

The gravitomagnetic term in the equation of motion is just one of several velocity-dependent contributions to the whole [4]. It is physically unrealistic to adjust the strength of a single interaction term without simultaneously examining changes to other terms in the velocity

transformation package. Self-consistent transformations of the velocity-dependent terms from one frame to another in a metric framework have been worked out [5], and strongly constrained by experiment at well below the 0.1% level relevant to this discussion [6, 7].

It is clear that the choice of reference frame affects the lunar orbit shape needed to fit the LLR ranging data—and specifically the gravitomagnetic interaction’s contribution to that frame-dependent orbit [8]. Also clear is that current successful LLR analysis performed in the SSB frame requires inclusion of general relativity’s prescribed gravitomagnetism. Therefore, this interaction cannot be arbitrarily adjusted—alone or together with other aspects of post-Newtonian gravity—without considering the impact of such adjustments on LLR as well as on the variety of other relevant observations such as ranging to Mars and Mercury, binary pulsar pulse arrival times, etc.

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- [1] T. W. Murphy, Jr., K. L. Nordtvedt, and S. G. Turyshev, *Phys. Rev. Lett.* **98**, 071102 (2007).
- [2] J. G. Williams, S. G. Turyshev, D. H. Boggs, arXiv:gr-qc/0507083
- [3] E. M. Standish and J. G. Williams, “Orbital Ephemerides of the Sun, Moon, and Planets,” Chap. 8 of “Explanatory Supplement to the American Ephemeris and Nautical Almanac,” 4th ed., P. K. Seidelmann, ed., in press (2007).
- [4] J. G. Williams, X. X. Newhall, and J. O. Dickey, *Phys. Rev. D* **53**, 6730 (1996).
- [5] C. M. Will, & K. Nordtvedt, *Astrophys. J.*, **177**, 757 (1972)
- [6] J. Müller, K. L. Nordtvedt, and D. Vokrouhlicky, *Phys. Rev. D* **54**, R5927 (1996).
- [7] K. Nordtvedt, *Astrophys. J.*, **320**, 871 (1987)
- [8] S. M. Kopeikin, arXiv:gr-qc/0702120v2, (2007).